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Description

METHOD FOR DETERMINING A LONGITUDINAL VEHICLE VELOCITY BY COMPENSATING INDIVIDUAL WHEEL SPEEDS

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] The present invention claims priority to provisional application no. 60/450,248, filed on February 26, 2003, and is related to Attorney Docket No. 201-1057/FGT-1780PA), filed simultaneously herewith, the disclosure of which is incorporated by reference.

BACKGROUND OF INVENTION

[0002] The present invention relates generally to dynamic control systems for automotive vehicles and, more specifically to a system that compensates wheel speed sensor signals to determine a vehicle reference velocity.

[0003]

It is a well-known practice to control various operating dynamics of a motor vehicle to achieve active safety. Examples of active safety systems include traction control, yaw stability control and roll stability control systems. A more recent development has been to combine all the available subsystems to achieve better vehicle safety and dynamics performance. The effective operation of the various control systems requires high-accuracy and fast-response-times in the determination of the

operating states of the vehicle, regardless of road conditions and driving conditions. Such vehicle operating states include the vehicle longitudinal, lateral and vertical velocities measured along the body-fixed longitudinal, lateral and vertical axes, the attitude of the vehicle body, and the travel course of the vehicle.

[0004] One piece of basic information that forms the afore-mentioned vehicle state estimation is the linear velocity of the rotating centers of the four wheels. For example, this information can be used to assess the wheel slip used in anti-brake-lock controls and traction controls and to estimate the longitudinal velocity of the vehicle. In order to obtain the linear corner velocities, the wheel speed sensors are used. The wheel speed sensors output the products of the wheel rotational speeds and the rolling radii. The wheel rotational speeds are directly measured and the rolling radii are assumed their nominal values. During dynamic maneuvers, the variations of the wheel normal loading will affect the rolling radii. Hence, the nominal rolling radii may not reflect the actual rolling radii and thus cause errors in the calculation of the wheel speeds.

[0005] It would, therefore be desirable to provide a more accurate way in which to determine the vehicle speed taking into consideration changes in rolling radii.

SUMMARY OF INVENTION

[0006] The present invention provides an improved determination of the individual wheel speeds. In the present invention the individual wheel speed calculations may be compensated for by learning the rolling radii of

the wheels. Thus, a more accurate determination of the vehicle reference velocity or the longitudinal velocity may be determined.

[0007] In one aspect of the invention, a control system 24 for controlling a safety system 40 of an automotive vehicle includes a plurality of wheel speed sensors 30 generating a plurality of wheel velocity signals, a steering angle sensor 39 generating a steering actuator angle signal, a yaw rate sensor 28 generating a yaw rate signal, a lateral acceleration sensor 32 generating a lateral acceleration signal and a controller 26. The controller 26 generates a final reference vehicle velocity in response to the plurality of wheel speed signals, the steering angle signal, the yaw rate signal and the lateral acceleration signal. The controller 26 controls the safety system in response to the final reference vehicle velocity.

[0008] In a further aspect of the invention, a method of controlling a safety system for an automotive vehicle having a plurality of wheels includes determining a plurality of wheel velocities for the plurality of wheels, determining a preliminary longitudinal velocity of the vehicle from the plurality of wheel velocities, determining a plurality of correction factors for the plurality of wheel velocities for the plurality of wheels, determining a vehicle reference velocity in response to the plurality of correction factors, the plurality of wheel velocities and the preliminary longitudinal velocity, determining a lateral acceleration, determining a vehicle reference velocity correction factor in response to the lateral acceleration, determining a final reference velocity in response to the vehicle reference velocity correction factor and the vehicle reference velocity, and controlling the safety system

in response to the final reference velocity.

[0009] Other advantages and features of the present invention will become apparent when viewed in light of the detailed description of the preferred embodiment when taken in conjunction with the attached drawings and appended claims.

BRIEF DESCRIPTION OF DRAWINGS

[0010] Figure 1 is a top view of a motor vehicle illustrating various operating parameters of a vehicle experiencing a turning maneuver on a road surface.

[0011] Figure 2 is a side view of a motor vehicle wheel illustrating various operating parameters of the wheel.

[0012] Figure 3 is a block diagram showing a portion of a microprocessor interconnected to sensors and controlled devices, which may be included in a system according to the present invention.

[0013] Figure 4 is a control system block diagram in accordance with the present invention.

DETAILED DESCRIPTION

[0014] In the following figures the same reference numerals will be used to illustrate the same components.

[0015]

Referring now to Figure 1, various operating parameters and variables used by the present invention are illustrated as they relate to the application of the present invention to a ground based motor vehicle 10

having wheels 12, 14, 16, 18. Those skilled in the art will immediately recognize the basic physics represented by these illustrations, thereby making the adaptation to different types of vehicles easily within their reach. A lateral and longitudinal velocities of the center of gravity are denoted as V_x and V_y a yaw angular rate is denoted as ω_x, a front wheel steering angle is denoted as δ, lateral acceleration is represented by a_y, longitudinal acceleration is represented by a_x.

[0016]

Using those vehicle motion variables, the velocities of the vehicle at the four corner locations, where the wheels are attached to the vehicle, can be calculated in the following form which are projected along the body fixed longitudinal and lateral directions

$$\begin{aligned} V_{lfx} &= V_x - \omega_z t_f, \quad V_{lfy} = V_y + \omega_z l_f \\ V_{rfx} &= V_x + \omega_z t_f, \quad V_{rfy} = V_y + \omega_z l_f \\ V_{lrx} &= V_x - \omega_z t_r, \quad V_{lry} = V_y - \omega_z l_r \\ V_{rrx} &= V_x + \omega_z t_r, \quad V_{rry} = V_y - \omega_z l_r \end{aligned} \tag{1}$$

where t_f and t_r are the half tracks for the front and rear axles, l_f and l_r are the distances between the center of gravity of the vehicle and the front and rear axles. The variables V_{lf}, V_{rf}, V_{lr} and V_{rr} are the linear velocities of the four corners along the wheel heading directions (left front, right front, left rear and right rear, respectively), which can be calculated as in the following

$$
\begin{aligned}
V_{lf} &= V_{lfx}\cos(\delta) + V_{lfy}\sin(\delta) \\
V_{rf} &= V_{rfx}\cos(\delta) + V_{rfy}\sin(\delta) \\
V_{lr} &= V_{lrx} \\
V_{rr} &= V_{rrx}
\end{aligned}
\tag{2}
$$

[0017] Referring now to Figure 2, vehicle corner velocity along the wheel longitudinal direction is equal to the sum of the contact patch slip velocity v_{cp} and the product of the wheel rotational rate ω_{whl} and its rolling radius r_0.

[0018] Referring now to Figure 3, stability control system 24 has a controller 26 used for receiving information from a number of sensors which may include a yaw rate sensor 28, speed sensors 30 (at each wheel), a lateral acceleration sensor 32, a roll rate sensor 34, a steering angle (hand wheel position) sensor 35, a longitudinal acceleration sensor 36, a pitch rate sensor 37, and steering angle position sensor 39. Steering angle position sensor 39 senses the position of the steered road wheels. Lateral acceleration, longitudinal acceleration, yaw rate, roll orientation and speed may also be obtained using a global positioning system (GPS). Based upon inputs from the sensors, controller 26 controls the safety system 40. Depending on the desired sensitivity, the type of safety system and various other factors, not all the sensors 28-39 may be used in a commercial embodiment. Other factors may be obtained from the sensors such as the surface mu and the vehicle side slip angle, β.

[0019]

Roll rate sensor 34 and pitch rate sensor 37 may sense the roll condition to be used with a rollover control system as an extension of the present

application.

[0020] Safety system 40 may be a number of types of safety systems including a roll stability control system, a yaw control system, antilock brakes, traction control, airbags, or active suspension system.

[0021] Safety system 40 if implemented may control a position of a front right wheel actuator, a front left wheel actuator, a rear left wheel actuator, or a right rear wheel actuator. Although, as described above, two or more of the actuators may be simultaneously controlled as one actuator. Based on the inputs from sensors 28 through 39, controller 26 determines the vehicle dynamic conditions and controls the safety system. Controller 26 may also use brake control coupled to front right brakes, front left brakes, rear left brakes, and right rear brakes to dynamically control the vehicle. By using brakes in addition to steering control some control benefits may be achieved. For example, yaw control and rollover control may be simultaneously accomplished.

[0022] Speed sensor 30 may be one of a variety of speed sensors known to those skilled in the art. For example, a suitable speed sensor may include a sensor at every wheel that is averaged by controller 26. As will be described below, the controller 26 translates the wheel speeds into the speed of the vehicle.

[0023]

Referring now to Figure 4, a method of operating a safety system using a corrected vehicle velocity is determined. In step 60 the wheel speed sensors are read. In one embodiment each wheel has a separate speed

sensor.

[0024] The wheel speed sensor outputs usually are calibrated for providing the linear directional velocities V_{lf}, V_{rf}, V_{lr} and V_{rr} by multiplying the wheel rotational angular speeds with a nominal rolling radius of the wheels. The variables $\omega_{lf\text{-}sensor}$, $\omega_{rf\text{-}sensor}$, $\omega_{lr\text{-}sensor}$ and $\omega_{rr\text{-}sensor}$ are the wheel angular velocity at the left-front corner, right-front corner, left-rear corner and rear-right corner respectively. The nominal rolling radius (typically used in ABS) for calculating wheel speeds from the wheel rotational rates is r_0. Thus, the linear directional velocities may be represented by:

$$\begin{aligned} v_{lf} &= \omega_{lf-sensor} r_0 \\ v_{rf} &= \omega_{rf-sensor} r_0 \\ v_{lr} &= \omega_{lr-sensor} r_0 \\ v_{rr} &= \omega_{rr-sensor} r_0 \end{aligned} \qquad (3)$$

[0025] Notice that the wheels have different rolling radii than r_0. Hence, in order to accurately calculate the actual linear velocities at the four corners, correction factors need to be added. The individual correction factors are denoted as K_{lf}, K_{rf}, K_{lr} and K_{rr} for the left-front, right-front, left-rear and rear-right corners, respectively. Thus, the linear directional velocities may then be represented by:

$$\begin{aligned} v_{lf} &= \kappa_{lf} \omega_{lf-sensor} r_0 \\ v_{rf} &= \kappa_{rf} \omega_{rf-sensor} r_0 \\ v_{lr} &= \kappa_{lr} \omega_{lr-sensor} r_0 \\ v_{rr} &= \kappa_{rr} \omega_{rr-sensor} r_0 \end{aligned} \qquad (4)$$

[0026] Notice also that the wheels experience not only the rotational motion but

also the linear sliding motion, or longitudinal slip. The slip is caused by the relative motion between the wheel and the road at the contact patch (CP). The longitudinal velocities of the relative motions at the contact patches are denoted as $v_{cp\text{-}lf}$, $v_{cp\text{-}rf}$, $v_{cp\text{-}lr}$ and $v_{cp\text{-}rr}$, then the vehicle corner velocities can be expressed as the sums of two speeds as in the following

$$\begin{aligned} V_{lf} &= v_{cp-lf} + v_{lf} \\ V_{rf} &= v_{cp-rf} + v_{rf} \\ V_{lr} &= v_{cp-lr} + v_{lr} \\ V_{rr} &= v_{cp-rr} + v_{rr} \end{aligned} \tag{5}$$

[0027]

The longitudinal and lateral velocities of the vehicle may be determined in step 62 from the sensors, or they may be calculated as in Ford disclosure 201-1057 (Attorney Docket No. FGT-1780 PA) filed simultaneously herewith, or even a rough estimation by averaging certain variables calculated from wheel speeds. This may be a rough estimate or average but, as mentioned above, does not take into consideration the rolling radius or other factors. Consider

$$V_y = V_x \tan(\beta) \tag{6}$$

where βis the vehicle side slip angle V_y is the lateral velocity of the vehicle and V_x is the longitudinal velocity of the vehicle. In step 64, the front steering angle 8 is determined. Then, the individual correction factors K_{lf}, K_{rf}, K_{lr} and K_{rr} for each wheel can be calculated in step 66 as

$$\kappa_{lf} = \frac{V_x[\cos(\delta)+\tan(\beta)\sin(\delta)] + \omega_z[l_f\sin(\delta) - t_f\cos(\delta)]}{\omega_{lf-sensor} r_0} - \frac{v_{cp-lf}}{\omega_{lf-sensor} r_0}$$
$$\kappa_{rf} = \frac{V_x[\cos(\delta)+\tan(\beta)\sin(\delta)] + \omega_z[l_f\sin(\delta) + t_f\cos(\delta)]}{\omega_{rf-sensor} r_0} - \frac{v_{cp-rf}}{\omega_{rf-sensor} r_0}$$
$$\kappa_{lr} = \frac{V_x - \omega_z t_r}{\omega_{lr-sensor} r_0} - \frac{v_{cp-lr}}{\omega_{lr-sensor} r_0}$$
$$\kappa_{rr} = \frac{V_x + \omega_z t_r}{\omega_{rr-sensor} r_0} - \frac{v_{cp-rr}}{\omega_{rr-sensor} r_0} \qquad (7)$$

[0028] The product term tan(β)sin(δ) is negligible in comparison to cos(δ), hence equation (7) may be further simplified to the following, which is independent of the vehicle side slip angle β

$$\kappa_{lf} \approx \frac{V_x\cos(\delta) + \omega_z[l_f\sin(\delta) - t_f\cos(\delta)]}{\omega_{lf-sensor} r_0} - \frac{v_{cp-lf}}{\omega_{lf-sensor} r_0}$$
$$\kappa_{rf} \approx \frac{V_x\cos(\delta) + \omega_z[l_f\sin(\delta) + t_f\cos(\delta)]}{\omega_{rf-sensor} r_0} - \frac{v_{cp-rf}}{\omega_{rf-sensor} r_0} \qquad (8)$$
$$\kappa_{lr} = \frac{V_x - \omega_z t_r}{\omega_{lr-sensor} r_0} - \frac{v_{cp-lr}}{\omega_{lr-sensor} r_0}$$
$$\kappa_{rr} = \frac{V_x + \omega_z t_r}{\omega_{rr-sensor} r_0} - \frac{v_{cp-rr}}{\omega_{rr-sensor} r_0}$$

[0029]

In the case of small wheel longitudinal slip ratios, the longitudinal velocities v_{cp-lf}, v_{cp-rf}, v_{cp-lr} and v_{cp-rr} of the relative motions at the contact patches are close to zero, and equation (8) can be further simplified as the following

$$\kappa_{lf} \approx \frac{V_x \cos(\delta) + \omega_z [l_f \sin(\delta) - t_f \cos(\delta)]}{\omega_{lf-sensor} r_0}$$

$$\kappa_{rf} \approx \frac{V_x \cos(\delta) + \omega_z [l_f \sin(\delta) + t_f \cos(\delta)]}{\omega_{rf-sensor} r_0} \qquad (9)$$

$$\kappa_{lr} = \frac{V_x - \omega_z t_r}{\omega_{lr-sensor} r_0}$$

$$\kappa_{rr} = \frac{V_x + \omega_z t_r}{\omega_{rr-sensor} r_0}$$

[0030]

The digital value of the above wheel speed individual correction factors K_{lf}, K_{rf}, K_{lr} and K_{rr} at the time instant t=kΔT are

$\kappa_{lf_k}, \kappa_{rf_k}, \kappa_{lr_k}$ and κ_{rr_k},

then learning algorithms can be used to calculate the average correction factors. The correction factors are determined using an iterative process that is updated every N calculation samples in the following learning example. Notice that this is a conditional computation which is conducted only if the wheel''s longitudinal slip ratios are small.

$$
\begin{aligned}
&START\\
&if \quad k < N\\
&\quad \bar{\kappa}_{lf_{k+1}} = \bar{\kappa}_{lf_k} + \frac{\kappa_{lf_{k+1}}}{N}\\
&\quad \bar{\kappa}_{rf_{k+1}} = \bar{\kappa}_{rf_k} + \frac{\kappa_{rf_{k+1}}}{N}\\
&\quad \bar{\kappa}_{lr_{k+1}} = \bar{\kappa}_{lr_k} + \frac{\kappa_{lr_{k+1}}}{N}\\
&\quad \bar{\kappa}_{rr_{k+1}} = \bar{\kappa}_{rr_k} + \frac{\kappa_{rr_{k+1}}}{N}\\
&\quad k = k+1\\
&elseif \quad k = N\\
&\quad k = 0\\
&\quad \bar{\kappa}_{lf} = \bar{\kappa}_{lf_{N+1}}\\
&\quad \bar{\kappa}_{rf} = \bar{\kappa}_{rf_{N+1}}\\
&\quad \bar{\kappa}_{lr} = \bar{\kappa}_{lr_{N+1}}\\
&\quad \bar{\kappa}_{rr} = \bar{\kappa}_{rr_{N+1}}\\
&\quad go \quad to \quad START
\end{aligned}
\tag{10}
$$

[0031] Using the above learning algorithm, corrected wheel speeds at each wheel can be determined in step 66 based upon the learned correction factor.

$$
\begin{aligned}
\hat{v}_{lf_k} &= \bar{\kappa}_{lf}\, r_0 \omega_{lf-sensor_k}\\
\hat{v}_{rf_k} &= \bar{\kappa}_{rf}\, r_0 \omega_{rf-sensor_k}\\
\hat{v}_{lr_k} &= \bar{\kappa}_{lr}\, r_0 \omega_{lr-sensor_k}\\
\hat{v}_{rr_k} &= \bar{\kappa}_{rr}\, r_0 \omega_{rr-sensor_k}
\end{aligned}
\tag{11}
$$

[0032]

Notice that the above learning algorithm only corrects the individual wheel speeds. There are cases when the average rolling radii of the four wheels are reduced together due to vehicle loading change. Feeding back the above corrected wheel speeds to the algorithms used in vehicle dynamics

control will provide a vehicle reference velocity

$$\hat{V}_{ref}$$

in step 70 which needs to be further calibrated against the available vehicle longitudinal acceleration sensor signal.

[0033] Consider that the actual vehicle reference velocity is

$$V_{ref} = \kappa \hat{V}_{ref} \tag{12}$$

where κ is the global correction factor due to the total vehicle loading. κis usually a slow time varying parameters

$$\kappa \dot{\hat{V}}_{ref} = a_x - g\theta_y \tag{13}$$

where θ_y is the vehicle pitch angle generated from a pitch angle sensor or calculated from the pitch rate sensor signal.

[0034] In step 72, the longitudinal acceleration a_x is determined. Then, the following variables are defined

$$\hat{V} = \begin{bmatrix} \hat{v}_{ref_1} \\ \hat{v}_{ref_2} \\ \vdots \\ \hat{v}_{ref_N} \end{bmatrix}, \quad A_x = \begin{bmatrix} a_{x_1} \\ a_{x_2} \\ \vdots \\ a_{x_N} \end{bmatrix}, \quad \Theta_y = \begin{bmatrix} \theta_{y_1} \\ \theta_{y_2} \\ \vdots \\ \theta_{y_N} \end{bmatrix} \tag{14}$$

[0035]

Then a least square computation of the correction factor due to loading can be determined in step 74 as the following:

$$\hat{\kappa} = inv(\hat{V}^T \hat{V})\hat{V}^T [A_x - g\Theta_y] \tag{15}$$

or in the following form

$$\hat{\kappa} = \frac{\sum_{k=M+1}^{M+N} \hat{v}_{ref_k}(a_{x_k} - g\theta_{y_k})}{\sum_{k=M+1}^{M+N} \hat{v}_{ref_k}{}^2} \tag{16}$$

[0036] Notice that the global correction factor

$\hat{\kappa}$

is updated every N computational samples when the wheels have small longitudinal slip ratios. The digital implementation of equation (16) can be obtained as in the following where V_{k+1} is the updated reference velocity determined in step 76.

$$\begin{aligned}
&START \\
&if\ k < N \\
&\quad A_{k+1} = A_k + \hat{v}_{ref_{k+1}}(a_{x_{k+1}} - g\theta_{y_{k+1}}) \\
&\quad V_{k+1} = V_k + \hat{v}_{ref_{k+1}}\hat{v}_{ref_{k+1}} \\
&\quad k = k+1 \\
&elseif\quad k = N \\
&\quad \hat{\kappa} = \frac{A_{N+1}}{V_{N+1}} \\
&\quad k = 0 \\
&\quad go\quad to\quad START
\end{aligned}$$

[0037]

The final corrected wheel speed sensor signals may be corrected by the aforementioned factors can also be obtained as the following:

$$
\begin{aligned}
\hat{v}_{lf_k} &= \hat{\kappa}\overline{\kappa}_{lf}\, r_0 \omega_{lf-sensor_k} \\
\hat{v}_{rf_k} &= \hat{\kappa}\overline{\kappa}_{rf}\, r_0 \omega_{rf-sensor_k} \\
\hat{v}_{lr_k} &= \hat{\kappa}\overline{\kappa}_{lr}\, r_0 \omega_{lr-sensor_k} \\
\hat{v}_{rr_k} &= \hat{\kappa}\overline{\kappa}_{rr}\, r_0 \omega_{rr-sensor_k}
\end{aligned}
\qquad (17)
$$

[0038] Once the corrected final vehicle reference velocity is determined, the safety system 40 may be controlled using the compensated velocity values.

[0039] While particular embodiments of the invention have been shown and described, numerous variations and alternate embodiments will occur to those skilled in the art. Accordingly, it is intended that the invention be limited only in terms of the appended claims.